Depth-First Search

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Abstract

Depth-first search of a graph is formalized with function. It is shown that it visits all of the reachable nodes from a given list of nodes. Executable ML code of depth-first search is obtained with code generation feature of Isabelle/HOL. The formalization contains two implementations of depth-first search: one by stack and one by nested recursion. They are shown to be equivalent. The termination condition of the version with nested-recursion is shown by the method of inductive invariants.

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1 Depth-First Search

theory DFS imports Main begin

1.1 Definition of Graphs

typedecl node
type-synonym graph = (node * node) list

primrec nexts :: [graph, node] ⇒ node list where
   nexts [] n = []
   | nexts (e#es) n = (if fst e = n then snd e # nexts es n else nexts es n)
definition nextss :: [graph, node list] ⇒ node set
where nextss g xs = set g "" set xs

lemma nextss-set: y ∈ set (nexts g x) = ((x,y) ∈ set g)
by (induct g) auto

lemma nextss-Cons: nextss g (x#xs) = set (nexts g x) ∪ nextss g xs
unfolding nextss-def by (auto simp add: Image-def nexts-set)

definition reachable :: [graph, node list] ⇒ node set
where reachable g xs = (set g)∗ "" set xs

1.2 Depth-First Search with Stack

definition nodes-of :: graph ⇒ node set
where nodes-of g = set (map fst g @ map snd g)

lemma [simp]: x ∉ nodes-of g ⇒ nexts g x = []
by (induct g) (auto simp add: nodes-of-def)

lemma [simp]: finite (nodes-of g − set ys)
proof (rule finite-subset)
  show finite (nodes-of g)
  by (auto simp add: nodes-of-def)
qed (auto)

function
dfs :: graph ⇒ node list ⇒ node list ⇒ node list
where
  dfs-base: dfs g [] ys = ys
| dfs-inductive: dfs g (x#xs) ys = (if List.member ys x then dfs g xs ys
else dfs g (nexts g x@xs) (x#ys))
by pat-completeness auto

termination
apply (relation inv-image (finite-psubset <*lex*> less-than)
  (λ(g,xs,ys). (nodes-of g − set ys, size xs)))
apply auto[1]
apply (simp-all add: finite-psubset-def)
by (case-tac x ∈ nodes-of g) (auto simp add: List.member-def)

• The second argument of dfs is a stack of nodes that will be visited.
• The third argument of dfs is a list of nodes that have been visited already.
1.3 Depth-First Search with Nested-Recursion

function
dfs2 :: graph ⇒ node list ⇒ node list ⇒ node list

where
dfs2 g [] ys = ys
| dfs2-inductive:
dfs2 g (x#xs) ys = (if List.member ys x then dfs2 g xs ys
else dfs2 g xs (dfs2 g (nexts g x) (x#ys)))

by pat-completeness auto

lemma dfs2-invariant: dfs2-dom (g, xs, ys) ⇒ set ys ⊆ set (dfs2 g xs ys)
by (induct g xs ys rule: dfs2.pinduct) (force simp add: dfs2.psimps)+

termination dfs2
apply (relation inv-image (finite-psubset <*lex*> less-than)
(λ(g,xs,ys). (nodes-of g ⊆ set ys, size xs)))
apply auto[1]
apply (simp-all add: finite-psubset-def)
apply (case-tac x ∈ nodes-of g)
apply (auto simp add: List.member-def)[2]
by (insert dfs2-invariant) force

lemma dfs-app: dfs g (xs@ys) zs = dfs g ys (dfs g xs zs)
by (induct g xs zs rule: dfs.induct) auto

lemma dfs2 g xs ys = dfs g xs ys
by (induct g xs ys rule: dfs2.induct) (auto simp add: dfs-app)

1.4 Basic Properties

lemma visit-subset-dfs: set ys ⊆ set (dfs g xs ys)
by (induct g xs ys rule: dfs.induct) auto

lemma next-subset-dfs: set xs ⊆ set (dfs g xs ys)
proof (induct g xs ys rule:dfs.induct)
case (2 g x xs ys)
show ?case
proof (cases x ∈ set ys)
case True
have set ys ⊆ set (dfs g xs ys)
  by (rule visit-subset-dfs)
with 2 and True show ?thesis
  by (auto simp add: List.member-def)
next
  case False
  have set (x#ys) ⊆ set (dfs g (nexts g x @ xs) (x#ys))
    by (rule visit-subset-dfs)
with 2 and False show ?thesis
  by (auto simp add: List.member-def)
qed
qed(simp)

lemma nextss-closed-dfs [rule-format]:
nextss g ys ⊆ set xs ∪ set ys → nextss g (dfs g xs ys) ⊆ set (dfs g xs ys)
bys (induct g xs ys rule:dfs.induct, auto simp add:nextss-Cons List.member-def)

lemma nextss-closed-dfs: nextss g (dfs g xs []) ⊆ set (dfs g xs [])
bys (rule nextss-closed-dfs, simp add: nextss-def)

lemma Image-closed-trancl: assumes r " X ⊆ X shows r* " X = X
proof
  show r* " X ⊆ X
  proof
    { fix x y
      assume y: y ∈ X
      assume (y,x) ∈ r*
      then have x ∈ X
        by (induct) (insert assms y, auto simp add: Image-def)
    }
    then show ?thesis unfolding Image-def by auto
  qed
qed auto

lemma reachable-closed-dfs: reachable g xs ⊆ set(dfs g xs [])
proof
  have reachable g xs ⊆ reachable g (dfs g xs [])
    unfolding reachable-def by (rule Image-mono) (auto simp add: next-subset-dfs)
  also have ... = set(dfs g xs [])
    unfolding reachable-def
  proof (rule Image-closed-trancl)
    from nextss-closed-dfs
    show set g " set (dfs g xs []) ⊆ set (dfs g xs [])
      by (simp add: nextss-def)
  qed
  finally show ?thesis .
qed

lemma reachable-nexts: reachable g (nexts g x) ⊆ reachable g [x]
  unfolding reachable-def
by (auto intro: converse-rtrancl-into-rtrancl simp: nexts-set)

lemma reachable-append: reachable g (xs @ ys) = reachable g xs ∪ reachable g ys
  unfolding reachable-def by auto
lemma dfs-subset-reachable-visit-nodes: set (dfs g xs ys) ⊆ reachable g xs ∪ set ys
proof (induct g xs ys rule: dfs.induct)
  case 1
  then show ?case by simp
next
  case (2 g x xs ys)
  show ?case
  proof (cases x ∈ set ys)
    case True
    with 2 show set (dfs g (x#xs) ys) ⊆ reachable g (x#xs) ∪ set ys
     by (auto simp add: reachable-def List.member-def)
  next
  case False
  have reachable g (nexts g x) ⊆ reachable g [x]
    by (rule reachable-nexts)
  hence a: reachable g (nexts g x @ xs) ⊆ reachable g (x#xs)
    by (simp add: reachable-append, auto simp add: reachable-def)
  with False 2
  show set (dfs g (x#xs) ys) ⊆ reachable g (x#xs) ∪ set ys
    by (auto simp add: reachable-def List.member-def) blast
  qed
qed

1.5 Correctness

theorem dfs-eq-reachable: set (dfs g xs []) = reachable g xs
proof
  have set (dfs g xs []) ⊆ reachable g xs ∪ set []
    by (rule dfs-subset-reachable-visit-nodes[of g xs []])
  thus set (dfs g xs []) ⊆ reachable g xs
    by simp
qed (rule reachable-closed-dfs)

theorem y ∈ set (dfs g [x] []) = ((x,y) ∈ (set g)*)
  by (simp only:dfs-eq-reachable reachable-def, auto)

1.6 Executable Code

code-type node
  (SML int)

instantiation node :: equal
begin

definition equal-node :: node => node => bool
where
  [code del]: equal-node = (op =)

instance proof
qed \((simp add: equal-node-def)\)

end

code-const HOL.equal :: node ⇒ node ⇒ bool
\(\text{(SML } !((\cdot : \text{int}) = \cdot))\)

export-code dfs dfs2 in SML file dfs.ML

end